设计天堂

热带及亚热带地区考虑景观和生态系统工程的农村有机废水沼气生产

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【摘要】在热带和亚热带地区，第二代塘系统【1】包含了高效厌氧发酵器，能够显著改善河流水质。对于处理各种废水，如育肥猪场或市政废水，它的性价比很高，即在较低的建设和运行费用条件下可以达到较好的出水水质。而且厌氧过程提供了以甲烷为载体的能源，如果用来发电，则污水处理厂可以实现低 CO2 排放下的电力自给自足。与其它常用处理技术相比，这是另一个突出优点。另一个显著的特点是污水厂的运行不需要高素质人员。如果设计良好，并考虑到景观和生态因素，可以创造出具有生物多样性和自然风貌的生物栖息地。如果建设时尽量少用混凝土，建构筑物部分甚至全部被泥土覆盖，可以创造出非常令人满意的景色。

Designing Paradise

Rural organic wastewater for biogas production in sub-tropical and tropical areas, considering landscape ecology and biosystems engineering”

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SUMMARY

In the tropics and semi-tropics, pond systems of the second generation [1] consisting of anaerobic high-rate digesters can significantly contribute to improving the water quality of river basins.
If these plants are used to treat wastewater like from pig fattening stables or from municipalities a good treatment efficiency can be obtained at a low construction and operation cost.
Furthermore the anaerobic process provides enough energy in the form of methane gas, if converted to electricity, to run the plant selfsufficiently at low CO_2 emissions. This is another outstanding advantage when compared to the majority of other treatment options.

Fig. 1: Iguana (*Iguana iguana*) in the waste water treatment pond

Fig. 2: Waste water treatment pond

Remarkably no highly qualified personnel are required to operate the plant.
If well designed taking landscape and ecological aspects into account, biotopes of high biodiversity and natural appearance can be created.

A very satisfying appearance can be obtained, if concrete is used reluctantly in construction and structures are partly or even completely covered by earth.

1 Preface

The nutrition and the digestion system of humans are in principle identical when compared with pigs. This is in contrast to ruminant animals like cows.
In so far it can be assumed, that the results of the anaerobic treatment of pig manure can be applied to the treatment of municipal wastewater. Vice versa is of course also true.
The technology for the reliable operation of anaerobic digestion systems applicable for substrates like the excrements of animals consisting of manure and urine, also known as sludge, has in been principle developed for some time. This is also true in the case that other kinds of solid organic material like straw or “energy plants” are added.
However, if the sludge becomes diluted by adding water, this becomes very challenging: The sludge turns into wastewater with a high content of coarse suspended solids. This wastewater behaves fluid mechanically fundamentally very different when compared to sludge.
In order to treat this wastewater anaerobically in an economic manner under the leadership of the author at the Institute for Technology of the FAL Federal Research Centre in Agriculture at Braunschweig, Germany, – later named vTI and nowadays renamed into Thünen-Institute - intensive research and development activities were performed between the years 1981 to 1986. Finally it became obvious that the best solution as to the treatment of this kind of wastewater was in specially designed UASB-reactors [10]. At technical scale in 1987 this possibility was demonstrated by the author, first as brick construction in Columbia at the Corporación Autónoma del Valle de Cauca (CVC), Cali and thereafter in 1989 in Thailand at the Chiang Mai University (CMU), Energy Research and Development Institute-Nakornping (ERDI). These activities were part of the measures performed under the SEP Special Energy Programme of the GTZ German Technical Cooperation, which in 2011 merged to GIZ German International Cooperation. This technology can now be found according to [20] at more than 700 sites in Thailand. It had become very attractive to the farmers, so they made use of the technology transfer and dissemination measures which were offered. While the author was giving a presentation at a biogas-training course organized by the Biogas Institute of the Ministry of Agriculture (BIOMA) which was held in Chengdu (China in December 2012, [20] it was reported by participants from Thailand that the first demonstration plant, which was installed at the Mae Hia Research Centre of the CMU Chiang Mai University is still working after nearly 25 years of operation and is up to now being used for purposes of education.
To prove that the results and the experience gathered during a decade worth of work in research and development can also be applied to the treatment of municipal wastewater, in 1991 a plant for the treatment of municipal wastewater with a capacity of 120.000 population equivalents (P.E) was designed by the author for the City of Babahoyo, close to Guayaquil, Ecuador’s biggest harbour, while working for CES Consulting Engineers Salzgitter GmbH.
This was done after further development steps in reactor designs had been performed, successfully allowing the construction of UASB reactors to be done completely in concrete, whereby the UASB-plant for the 4-T-Farm at San Pathong, North Thailand should be mentioned [10]. This development became necessary as the UASB-design for digesters built in bricks is limited because of constraints in geometry and process technology to less than 200 m^3 digester volume, which with one unit will allow the treatment of about 3000 to 4000 P.E. of organic load.
Babahoyo is the capital of the province of “Los Rios” as well as the centre for commerce and – processing of all kinds of agricultural products of this region. Its agricultural productivity can hardly be topped, with up to three harvests per year depending on the sequence of cultures.
Consequently the wastewater of Babahoyo is characterized by small and medium sized agricultural and food processing industries like slaughterhouses. The plant had been evaluated for the first time during the 3 years between the years 2002 to 2004. The results and experiences are given below:
As the plant performed well and fulfilled all expectations they should be of interest especially for the treatment of diluted manure from pig stables and municipal wastewater in the southern regions of China.

2 Introduction

Nearly every year the city of Babahoyo in Ecuador was flooded by water from the river having the same name, Rio Babahoyo. During this period the inhabitants living in the centre of the city were fleeing to the second floor of their buildings. In the outskirts they had to travel by boat and were escaping into their houses which are resting on stilts.
Then, between Babahoyo and Ecuador's main harbour, Guayaquil, located 80 km southwards, an endless "sea of water" was expanding, which separated the city for weeks from any normal communication, leaving the boat as the only instrument for transport, traffic and communication.

However, notwithstanding all of this, what motivates the people to stay in the city of Babahoyo, is the extraordinary fertility of the surrounding alluvial soil, which allows the cultivation of rice, banana, cacao and the potential for cattle farming at an outstandingly high yield.
If more than 100,000 people are living under such conditions with an unsecured supply of potable water and waste as well as rain water drainage nearly non-existent, than it is not surprising, if terms referring to diseases like cholera, typhus, yellow fever and malaria are forming part of the common conversation and routine in and between the local clinics and hospitals.
Therefore it is more than understandable, that one day the idea within the framework of an international cooperation within the field of urban planning developed to reduce these serious deficits to a bearable level, if they can not be eliminated completely.
To this purpose, a corresponding contract was signed between the Ecuadorian Ministry of Housing and Construction (MIDUVI), the operator for water supply and water treatment, the enterprise of sanitation (EMSABA) and the KfW Kreditanstalt für Wiederaufbau, which – among others - was to ensure the finances for such a project.

Fig. 3: Little grebe
(*Tachybabtus ruficollis*)

Fig. 4: Methane bacteria [16]
(*Methanosarcina acetivorans)*

In 1991, the consortium ACB (Associación Consultores Babahoyo), under the leadership of the company CES Consulting Engineering Salzgitter, was awarded the contract to make the project come true.
The catalogue of measures comprised to surround the whole city with embankment works as a flood protection measure as well as to design and construct a well-organized water supply consisting of wells, water storage tower, potable water processing unit and corresponding water network. In addition the complete rainwater and wastewater drainage system including conveyor and treatment plant had to be designed and built.

3 Target specification of the wastewater treatment plant

While parts of the potable water network already existed, only fragments of the sewer network, split into many little drainage systems, had been build.
A central part of the total task therefore included the erection of the wastewater treatment plant by connecting and extending the existing sewer network fragments after previous rehabilitation, reconstruction and upgrading.

When the working group of engineers started to act, it immediately became clear, how the target specification of the wastewater treatment plant should be defined:

1. Treat as economic as possible the wastewater with regard to organic contamination and germs
2. Handle the resources - water, energy and nutrients - conservatively.
3. Designing the plant at lowest cost and under the consideration of the low level in education of the staff of the plant in order to allow its sustainable operation
4. Design the plant exemplary to disseminate this technology at similar places in Ecuador and neighbouring countries
5. Integrate the technical works into the landscape and the surrounding ecosystem

By means of a comparison of alternatives based on cost calculations – which also included the activated sludge process – following the suggestions of CES the decision by EMSABA and KfW was rapidly taken to select a process combination of anaerobic high-rate digesters followed by a series of wastewater treatment ponds (Fig. 7 and 8).
This approach was at that time unusual as normally only aerobic bacteria were used to treat municipal wastewater. In order to let the treatment process come true, the Consultant could make use of extensive fundamental works regarding the erection of high-rate reactors [2-12] and ponds [13-14], which he carried out for the implementation of previous projects at other locations.
However this time the main task to efficiently degrade the organic load of the wastewater should be performed by little anaerobic bacteria, such as methane bacteria forming part of the group of archaeabacteria (Fig. 4). They must have stood at the beginning of the biological evolution what was concluded by studying their genetic code and as they are characterized by unusual paths of metabolism [15-16].
That the methane, foreseen to be produced as a result of the wastewater treatment by anaerobic high rate reactors, should be used to generate electrical energy was seen by the design staff as a matter of course.
Not only economic aspects are in favour of this:
During the design phase it became obvious, that this would allow the treatment plant to become energetically autonomous. Especially the lifting station as the biggest energy consumer could be provided for with this source of bio-energy.
To achieve this became therefore an additional target specification of the design team:
Ultimately an energetically autonomous operation without disturbances and interruptions is the basis to assuring the constant clean up of a city often being affected by serious floods and to preserve a good hygienic status avoiding epidemics.

4 Construction

When the construction of the plant was progressing unfortunately conflicts were uprising concerning how the financial resources should be utilized.
Reasonably the financial resources should be split between the potable water supply and wastewater treatment so that in both fields the same degree regarding supply and proper disposal of the population is achieved.

The standard of some development banks even favours the disposal. The reason for this is based on the experience that the water supply can be improved and extended much easier when compared to the wastewater drainage, conveyance and especially the treatment works.
This is because of the fact, that the construction of a water supply system is, when compared to a wastewater drainage and treatment system, relatively simple and much cheaper, so that this activity can often also be performed well or at least in an acceptable manner by making use of local resources once the initial infrastructure has been erected professionally.

However, contrary to this fundamental principle in water policy in Babahoyo decisions were taken in favour of the extension of the water supply.
The driving force for this negative development might have been based on the political interest of parties involved at decision making level as potable water supply creates – especially in developing countries - votes, wastewater treatment does not. Another reason might have been the poor comprehension of the decision makers of the complex hygienic context.

Fig. 5: Netting fish in the aerobic wastewater treatment pond

Consequently, while the construction phase was progressing, more and more technical elements perfectly designed for the treatment plant became suspended by political decision in favour of an unplanned extension of the potable water supply system.

Among these measures, which were not performed have to be mentioned:

1. Two rooms for the installation and operation of an electrical power transformer and a bio-methane gas-energy-generator-set including piling foundation.
2. The acquisition of a sludge pump and a tractor driven tanker for transporting and applying the anaerobically stabilized excess sludge as liquid fertilizer in agriculture and in order to operate the flotation tanks.
3. The construction of a composting area to treat part of the anaerobically stabilized excess sludge to make use of it in agriculture in the form of solid aggregate which is capable of being strewn.
4. Equipping all anaerobic digesters with three-phase-separators, valves, feeding pipes, distribution channels, weirs and collecting channels for the effluent and
5. last but not least all equipment to collect and to make complete use of the bio-methane being produced for energy supply and to avoid global warming by methane emission caused by unused biogas.

Especially because of the insistence owed to a few local personalities as well as the Consultant at the end of a lot of struggle finally at least the body shell of the six anaerobic digesters could be built in fabric.
For the wastewater treatment plant at that time about 4 million Euro had to be invested. If one compares these costs to the investment cost needed in plant construction in Europe and considers its seize of 120.000 P.E., it becomes apparent, that the whole plant could have been built extremely cheap, if it would have been completed following the design, for which countless hours of valuable engineering work had already been spent.

5 Operation

In 1999 when the plant, with all these deficiencies, could finally be put into operation, this could only be done on a provisional basis without the anaerobic reactors, which were the core of the total system.
Without the acquisition and installation of the technical equipment mentioned above under point 4 and 5 they were simply not operational and started to deteriorate in the tropical climate.
However, in order to start, at least with training the local staff, the plant was operated for a period of two years in a manner for which it had not been designed. At that time it operated completely over-burdened as a two stage pond system, consisting of an anaerobic followed by an aerobic pond. They were arranged in two parallel lanes (Fig. 7). This lead to the undesired effect of huge amounts of sedimentable solids accumulating as sludge in the wastewater treatment ponds. This has to be considered, as future measurements may be performed in order to evaluate the efficiency of the total system.
However, during this phase of operation limited funds could finally be raised in order to equip at least three of the six anaerobic reactor shells with part of the corresponding technical equipment.
In addition funds could be raised in order to train the staff to operate this new technology and to evaluate the technical performance of the total wastewater treatment plant.
When the Consultant was contracted to perform this task, he noticed in the mid of 2001, that because of the severe deficiency of the installed equipment two of the three anaerobic reactors were non-operational.

Fig. 6: Fish caught by net

While these became rehabilitated under the supervision of the Consultant the main organic load arriving at the plant was conveyed untreated via a by-pass to the pond system.
Only the next assignment in Babahoyo at the end of 2001/beginning of 2002 allowed the start-up of the anaerobic reactors. At that time all the anaerobic reactors received the same flow and organic load (Tab. 1).
Even though during this time there was heavy tropical rainfall at Babahoyo the total flow went to all three reactors. Only 1% of this flow had to be by-passed due to hydraulic peak events caused by thunder storms and to be conveyed biologically untreated into the following treatment step, the flotation tank followed by the pond system.

Fig. 7: General layout of the WWTP Waste Water Treatment Plant Babahoyo (Top view)

6 Know-How-transfer, Evaluation of the results in operation

After all three reactors had been in operation for a period of about a half a year (Fig. 9, since July 2002) with raw wastewater, it became possible to start with the ordinary operation and evaluation of their biological process as well as the other treatment process steps of the total pond system. After another half a year of delay because of severe problems caused by the customs at the nearby harbour of Guayaquil the laboratory had meanwhile also arrived. This allowed then, to use it from the very beginning of that moment in addition to the very simple initial equipment in order to evaluate and to operate the process adequately.

6.1 Staff

The plant as designed by the Consultant was the first plant with anaerobic process technology to treat municipal wastewater in Ecuador.

Consequently an important task of the Consultant was, to train staff suitable for its operation.
This was done by means of five on-site missions. In summary: an engineer as operator, two chemist for the laboratories for potable and wastewater, different helpers, two gardeners and three watchmen as assisting staff were trained. Meanwhile the staff is capable of operating the plant autonomously. Due to their motivation, approximately 9.000 data about operation were collected monthly.

Among those were data about the inlet raw sewage flow, the biogas flow and results about the physical, chemical, biological and biochemical composition of the wastewater (Fig. 17) as well as the excess sludge being produced. The data were gathered in specially designed sheets to be processed further by a computer. Thereafter they were printed together with the obtained results for purposes of documentation.

6.2 Bioreactor performance

Fig. 8: Flotation tank with wastewater treatment ponds in the background

Fig. 9: Anaerobic high rate reactors

Part of the Consultant's job to be performed - besides the task of training and building capacity of the staff – was to obtain data about the operation of all three anaerobic bioreactors in order to be able to use them in the future as reference under comparable constraints for the dimensioning of further new anaerobic treatment plants and in order to encourage and accelerate the dissemination of this process especially in Ecuador.
For this purpose the inflow of the reactors R1, R2 and R3 was split differently. This was done in order to determine the performance of the reactors at different retention times and space loading rates.

6.2.1 Work program

In order to determine the efficiency of the anaerobic high-rate reactors, the work program is given in detail in Tab. 1 ordered in phases of operation and evaluation.
The aim during the first operation phase, phase I, was, to ensure that the bacteria had enough time to adapt to the composition of the wastewater and to accumulate enough living biomass in order to start with the first measurement to meter the performance of the reactors. According to the planning this should be done at a moderate retention time of 16 hours. This value is about 1.7 times longer when compared to the design value for the plant.
After this first phase of operation, the hydraulic and organic loading of the reactors should be raised step by step until it reaches a critical limit, in order to define the performance curve of the reactors, which is valid under the local constraints.
Even though the phases of and the adjustments for operation were carefully planned, there were some circumstances which were out of control of the Consultant leading to a deviation in the programme:

Fig. 10: Dragonfly (*Anisoptera*)

1. Although the plant was fed continuously for an extended period of time each day, it was fed discontinuously during the evening and the night hours, as then the pumps were switched off manually by the operator.
2. The high rate reactors received their inflow from time to time not from a weir system which was throttled, but unthrottled (see Table 2) as the throttles were removed.

Tab. 1: Working schedule and conditions of operation according to planning and as they were executed

Phase	Duration of operation			Highrate reactors			Operation of pumps
	Date		Months	R1	R3	R5	
				Retention time			
			h	h	h	h	-
Phase I							
Start up operating the reactors							
Planned	6.2001	12.2002	7,0	16,0	16,0	16,0	**continous**
Executed	**1.2002**	**6.2002**	6,0	**ca. 16,0**	**ca. 16,0**	**ca. 16,0**	**discontinous**
Phase I							
Planned	6.2002	11.2002	4,0	16,0	16,0	16,0	**continous**
Executed	**9.7.2002**	**2.11.2002**	4,0	**16,0**	**16,0**	**16,0**	**discontinous**
Phase II							
Planned	11.2002	3.2003	4,0	9,0	12,0	42,0	**continous**
Executed	**3.11.2002**	**31.3.2003**	3,5	**6,1**	**13,1**	**62,3**	**continous**
Phase III							
Planned	1.4.2003	1.8.2003	3,0	5,0	-	40,0	**continous**
Executed	**29.3.2003**	**21.11.2003**					
Phase III-A	**29.3.2003**	**20.6.2003**	**3,0**	5	-	30,3	**continous**
Phase III-B	**21.6.2003**	**21.11.2003**	**5,0**	6,3	-	26,7	**discontinous**
Phase IV							
Planned	1.8.2003	-	-	16,0	16,0	16,0	**continous**
Executed	**22.11.2003**	**10.9.2004**	9,0	**10,6**	**9,1**	**14,8**	**discontinous**

6.2.2 Results

6.2.2.1 Bioreactor performance

The results are presented in Tab. 2 together with the different operational conditions. They were obtained under the basic adjustments as shown in Tab. 1.
In Tab. 2 the inflow concentrations for COD, BOD_5, the measured retention times t_R, the treatment efficiencies η and the COD as well as BOD_5 - volumetric loading rates B_R are given. The rates were obtained by calculation.
For interpretation of the values it is mentioned that the metered values including the BOD_5 removal rates are reliable. However the absolute value of the metered BOD_5-values may have to be corrected slightly.
Because of the equipment the laboratory provided initially, only at the end of the evaluation period conditions could be created to start calibration of the BOD_5-instrument and to operate it according to the required international standard. The calibration programme was not finished before the process evaluation was finalized.
The results are illustrated in Fig. 13 regarding the main parameter, which is the COD.

Tab. 2: Biological performance of the reactors as well of the total treatment plant during different phases of evaluation

Phase and period of evaluation	Parameter	Abbreviation	Dim.	Anaerobic reactor			Pond		Type of operation	Configuration of weir
				R1	R2	R3	1 & 2	3 & 4	Pumping	Triangle weir with trottle valve
Phase I										
Inbetriebnahme										
6.2001	Retention time	t_R	h	ca.16,0	ca. 16,0	ca. 16,0	--	--	discontinuous	no
Phase I										
9.7.2002	Retention time	t_R	h	16,0	16,0	16,0	--	--	discontinuous	no
2.11.2002	Inflow	Q	m^3/d	--						
	Chem. Oxigen demand	COD	mg/l	276,6						
	Efficiency	η_{COD}	%	58,8	64,3	63,5	77,4	75,3		
	Efficiency	$\eta_{CODfilt}$	%	--	--	--	--	73,4		
	Volumetric loading rate	$B_{R,COD}$	kg/m^3.d	0,41	0,41	0,41				
	Biol. Oxigen demand	BOD_5	mg/l	158,0						
	Efficiency	η_{BOD5}	%	77,8	70,2	77,0	80,7	81,7		
	Efficiency	$\eta_{BOD5filt}$	%	--	--	--	--	--		
Phase II										
3.11.2002	Retention time	t_R	h	6,1	13,1	62,3	--	--	continuous	no
31.3.03	Inflow	Q	m^3/d	--						
	Chem. Oxigen demand	COD	mg/l	210,8						
	Efficiency	η_{COD}	%	67,4	69,2	70,1	78,4	73,7		
	Efficiency	$\eta_{CODfilt}$	%	82,5	85,5	76,1	--	84,6		
	Volumetric loading rate	$B_{R,COD}$	kg/m^3.d	0,83	0,39	0,08				
	Biol. Oxigen demand	BOD_5	mg/l	115,1						
	Efficiency	η_{BOD5}	%	65,9	62,2	65,9	56,4	70,5		
	Efficiency	$\eta_{BOD5filt}$	%	--	--	--	86,8	86,6		
Phase III										
III-A	Retention time	t_R	h	5,0	--	30,3			continuous	yes
29.3.03	Inflow	Q	m^3/d	9.103						
20.6.04	Chem. Oxigen demand	COD	mg/l	207,3						
	Efficiency	η_{COD}	%	52,2	--	72,5	74,2	73,4		
	Efficiency	$\eta_{CODfilt}$	%	--	--	--	--	82,9		
	Volumetric loading rate	$B_{R,COD}$	kg/m^3.d	1,00	--	0,16				
	Biol. Oxigen demand	BOD_5	mg/l	125,9						
	Efficiency	η_{BOD5}	%	62,8	-	54,9	60,0	69,2		
	Efficiency	$\eta_{BOD5filt}$	%	62,5	-	73,9	84,7	83,5		
III-B1	Retention time	t_R	h	5,4	--	24,0			discontinuous	yes
21.6.03	Inflow	Q	m^3/d	7.967						
9.9.03	Chem. Oxigen demand	COD	mg/l	323,9						
	Efficiency	η_{COD}	%	49,4	--	64,5	77,4	79,4		
	Efficiency	$\eta_{CODfilt}$	%	--	--	--	--	78,5		
	Volumetric loading rate	$B_{R,COD}$	kg/m^3.d	1,44		0,32				
	Biol. Oxigen demand	BOD_5	mg/l	223,2						
	Efficiency	η_{BOD5}	%	62,4	--	--	73,8	71,2		
	Efficiency	$\eta_{BOD5filt}$	%	68,5	--	--	--	75,0		
III-B2	Retention time	t_R	h	7,1	--	29,3			discontinuous	yes
10.9.03	Inflow	Q	m^3/d	6.239						
21.11.03	Chem. Oxigen demand	COD	mg/l	396,6						
	Efficiency	η_{COD}	%	59,7	--	68,9	72,8	78,3		
	Efficiency	$\eta_{CODfilt}$	%	--	--	--	--	87,4		
	Volumetric loading rate	$B_{R,COD}$	kg/m^3.d	1,34		0,32				
	Biol. Oxigen demand	BOD_5	mg/l	271,2						
	Efficiency	η_{BOD5}	%	--	--	--	--	68,3		
	Efficiency	$\eta_{BOD5filt}$	%	--	--	--	--	71,5		
Phase IV										
22.11.03	Retention time	t_R	h	10,6	9,1	14,8			discontinuous	no
4.9.04	Inflow	Q	m^3/d	7.896						
	Chem. Oxigen demand	COD	mg/l	342,9						
	Efficiency	η_{COD}	%	61,1	69,2	72,7	66,5	70,0		
	Efficiency	$\eta_{CODfilt}$	%	--	--	--	--	75,2		
	Volumetric loading rate	$B_{R,COD}$	kg/m^3.d	0,78	0,90	0,56				
	Biol. Oxigen demand	BOD_5	mg/l	189,4						
	Efficiency	η_{BOD5}	%	43,2	48,9	51,4	52,8	68,6		
	Efficiency	$\eta_{BOD5filt}$	%	47,6	--	52,0	--	75,9		

Two curves can be seen:

The first curve shows the result obtained by measurements when operating a pilot plant in Colombia [2-12]. This information was taken as reference for the dimensioning of the treatment plant in Babahoyo during the design phase [17].
Besides the volumetric loading rate $B_{R,COD,}$ the retention time t_R is important for dimensioning. The retention time t_R has an effect on the settling zone, which is located on top of the anaerobic-reactor and which is isolated from it by a three-phase-separator.
The evaluation showed, that the measured COD-concentration of the wastewater (see Tab. 2) was significantly lower as assumed in the design calculations (c_{COD} = 670 mg/l, c_{BOD5} = 400 mg/l). Because of this circumstance in this very special case the retention time t_R is as layout parameter of higher importance than the volumetric loading rate $B_{R, COD}$.
The plant has been designed hydraulically for a retention time of about 6 to 16 hours, whereby as an optimum point for operation 9.6 hours were selected.
Furthermore it was assumed, that at retention times between 2.4 and 4 hours the operation of the reactor would only be possible under very high penalties in performance, e.g. because of low contact time with the sludge bed and wash out of a part of the anaerobic biomass.
The results obtained did confirm the design considerations:

Fig. 11: Little grebe
(*Tachybabtus ruficollis*

Fig. 12: Vegetation at the banks

In the range between 6 and 16 hours chosen as layout for the design, on average a degradation in COD of 66%, which means of 2/3rd could be obtained.
Under the assumption, that the anaerobically degradable COD_a is at 72.5% of the total COD, this leads to the conclusion, that at this point of operation about 91% of the COD_a is already degraded. This measured value is exactly congruent with the considerations laid down in the design [17].
Furthermore it can be seen, that at volumetric loading rates $B_{R,COD}$ between 1.0 and 1.5 kg $COD/m^3.d$ at corresponding short retention times the efficiency of the reactor is clearly declining:

It was noted that even though the retention time was theoretically on average 5 hours, the real retention time considering an operation period of six hours for the lifting pumps of the plant was during that period only 2.3 hours. That the performance will significantly decline during such very short retention times had also already been predicted during the design phase (see [17]).

6.2.2.2 Process stability

Under process stability the resistance of the process against unusual events is understood. Such events are among others heavy tropical rainfalls, which can be of extremely high intensity and duration. These are not unusual in the Guayas Basin, where Babahoyo is located.
Furthermore in Babahoyo has to be considered that in contrary to the instructions given by the Consultant the feeding of the anaerobic reactors did happen partially discontinuously and under elimination of the throttled weir system.
This temporarily led to extremely high peak loadings regarding the hydraulically designed process elements like zones for sedimentation, overflow weirs, etc. and extremely short retention times. Values have been observed, these were temporarily below 2 hours.

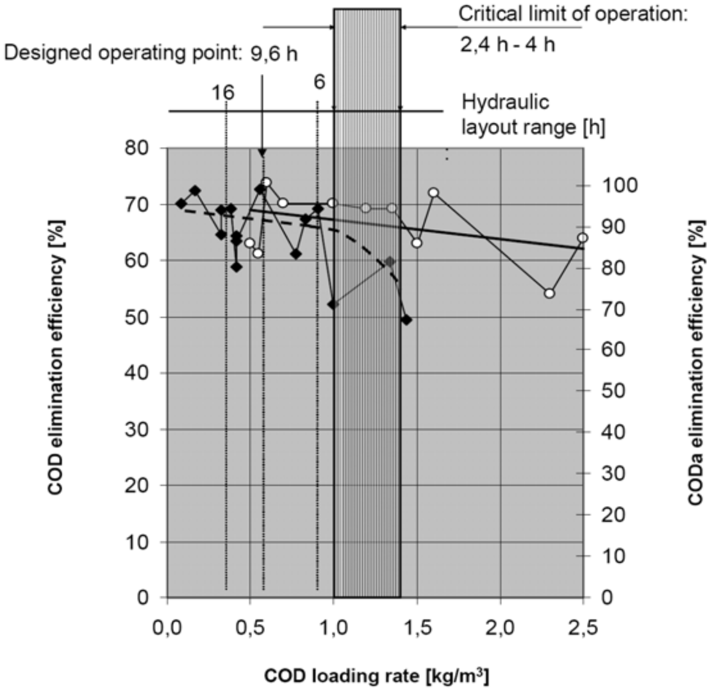

Fig. 13: COD performance diagram of the anaerobic highrate bioreactor: COD elimination efficiency versus COD loading rate

While the heavy rain events normally lasted a few hours and in some cases days, the erroneous conditions in operations covered a period of months.
Fortunately the evaluation of all these events shows, that during the entire period of plant operation the anaerobic biomass was never washed out even with very short retention times t_R, which would have caused the process to collapse. Consequently the anaerobic biological process performance has been very stable in the UASB reactors during all these years. The anaerobic bacteria never had to rebuild its population as in the initial start-up phase.

In conclusion, it can be said that by experience the biological process performed extremely stable. On the other hand it was of course observed that if the anaerobic reactors are being operated under conditions, which were not foreseen in the layout calculations for the design neither the reactors nor the total treatment plant perform in an optimum manner resulting in a reduced treatment efficiency.

Fig. 14: Red flycatcher

6.3 Plant performance

6.3.1 COD and BOD_5

Besides the performance of the anaerobic reactors the question: "How high is the total performance of the plant under optimum conditions of operation?" is of great interest.

Tab. 2 gives indications:

It shows, that at loading values present during the total evaluation period an effluent quality of the first two lagoons (pond 1 and 2) could be obtained, which varies – depending on the evaluation phase – between η_{COD} = 73% and 78% treatment efficiency.
There is an exception where some last measurements resulted in a 67% treatment efficiency. This value is most probably the effect of the discontinuous operation to the plant with a weir at the inlet, which in addition was not throttled.
The total efficiency of the plant during Phase IV was also low with a η_{COD} = 70 % measured as COD in the effluent of pond 3 and 4. During the previous phases it varied between 73 and 79%.
When comparing the COD and BOD_5 – effluent values of the anaerobic reactors with those of the ponds, it becomes obvious that there is no significant improvement regarding the treatment efficiency. Partially the effluent of the last pond cascade is even deteriorating when compared to the first pond cascade. This might be very surprising on the first view.

However, if the effluent is filtered, the filtered COD_{filt} values related to the COD-inlet concentration are about 10 % better when compared to the unfiltered COD and they continue to improve until the overflow weir at the outlet of the plant to 13 %.
This can be explained by the fact, that in the tropics and subtropics plankton rich in algae are responsible for a significant part of the remaining COD respectively BOD_5. This "negative" influence of algae on the effluent quality is much higher as can be observed under moderate climate conditions like in Germany.

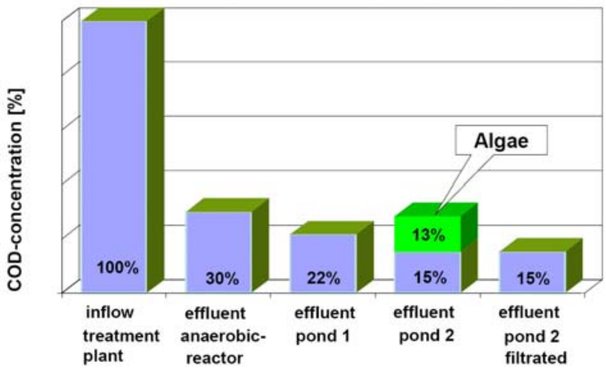

Fig. 15: Degradation of COD after selected treatment steps (on average)

In the tropics and subtropics, the processes of destruction and decay of organic material go hand in hand with the creation of new living biomass by photosynthesis. This is especially true in the last pond cascade of the pond system (see also Fig. 15).
Plankton biomass is bio-energy, generated from solar energy. Because of this, the idea came up to separate it by filtration in order to make use of it for the generation of energy products like biogas, which can be used in technical processes. However, because of economical limitations this could not be studied further at that time.

6.3.2 N and P

Besides the effluent of the treatment plant, if one studies the different nitrogen compounds of the pond systems, it becomes obvious that nitrification does occur.
This happened especially during the initial Phases I and II, when the plant had been operated more or less following the instructions given by the Consultant.

During the Phases III and IV the nitrification process slowed down, when compared to the previous phases of operation.
Consequently the ammonia content in the effluent of the first (pond 1 and 2) as well as the following pond cascade (pond 3 and 4) was increasing.

Fig. 16, Fig. 17 and Fig. 18: Sludge drying beds
with dewatering anaerobic excess sludge and rice harvest

This can be explained by the fact, that the operation of the pumps and the weirs of the plant did not follow the instructions given by the Consultant. Therefore about one quarter of the wastewater was discharged without any treatment directly into the ponds. In addition because of errors in operation, excess anaerobic sludge from the digesters has been washed out into the ponds, as it was not discharged in sufficient quantity into the sludge drying beds.
Because of this kind of plant operation the ponds were burdened with an additional organic load when compared to the design.
Furthermore as a portion of these organic loads consisted of sedimentable solids, they started to build a layer of sludge on the bottom reducing the total process reaction volume of the wastewater treatment ponds.
This amount of sedimentable solids has to be eliminated immediately, in order to reinstall the full treatment capability of the plant.
When the fish in pond 3 and 4 were caught by net in the autumn of the year 2004 it was noticed, that the sludge level in the ponds had already reached a height of half a meter above the original bottom.
This time the results of fishing when compared to the previous years (Fig. 5) were negative. This bio indicator proves in addition the negative effect of an inadequate operation of the anaerobic digesters with regard to the wastewater treatment process of the total system.
The observations regarding the parameter of phosphorous, which, besides nitrogen, was monitored, do not allow for a final conclusion to be drawn.

6.3.3 Effect of hygiene

If the treated wastewater is discharged – as it had been practiced for part of this flow - into little conveyors and channels for the purpose of irrigation in agriculture at the experimental fields of the treatment plant’s real estate then the concentration of germs in the effluent of the plant can be of importance.

This is valid especially in the case, that the water course is used for bathing purposes.
When measuring the water quality of the plant, during Phases I and II, a concentration of coliforms in the inflow of the plant of 10^7/100 ml was measured. At the outlet of the plant the value of this concentration had decreased to 10^4/100 ml.
These measurements are in line with various observations and reports in literature, among those of the WHO World Health Organisation.
They again confirm the excellent hygienization efficiency of naturally aerated wastewater treatment ponds.
This treatment efficiency had been controlled thereafter by the Ecuadorian Ministry of Urban Development MIDUVI (Ministerio de Urbanisación y Vivienda) and could be reconfirmed during Phase IV of operation in March 2004.

Fig. 19: Two bon vivant of real Ecuadorian coffee prepared on biogas!

The effluent quality obtained was far below the effluent quality standards which had come into force at that time [18]. This is also true for the previously mentioned parameters like N, P, COD and BOD_5.

6.4 Agricultural reuse of the sludge and the wastewater

Considering that the region surrounding Babahoyo is characterized by intensive agriculture, it is of outstanding interest to reuse the sludge and the treated wastewater as fertilizer and for irrigation purposes. This allows the preservation of these resources and is of economic interest.

Therefore the Consultant asked the operator to execute different tests for orientation and demonstration purposes with maize and rice to encourage farmers in its reuse (Fig.18). These tests were successful, as could be proven by the yields which were obtained. However this did not have any positive effect considering the involvement of the Universities at Babahoyo and Guayaquil as possible suitable institutions for the dissemination and application of these results at a broader scale. One reason was that in Babahoyo the local Agricultural University did not operate for a long period of time because of strikes. Another reason was that the budget for the evaluation measure of the wastewater treatment plant was very limited and this was also the case at the Universities. Therefore no further scientific and dissemination activities could be developed.
The excess anaerobic sludge, which, besides being part of the effluent of the treatment plant, was applied to the different cultures, and showed excellent dewatering characteristics as is demonstrated in Fig. 16 and 17.

6.5 R&D Research and Development

The cooperation between the operator of the treatment plant and the Technical University of Braunschweig (TUBS), Institute for Sanitary Engineering was fruitful. At TUBS a diploma thesis could be conducted with success. This work focused on the definition of a compact wastewater treatment process, which could replace the pond system (Fig. 21) in case not enough space is available to apply the treatment system chosen for Babahoyo and to purify the effluent of the anaerobic treatment step even better. It was proven, that these goals can be achieved. However, the penalty for this is a sharp increase in energy demand.

Fig. 20: Daily sampling

Fig. 21: Pilot plant of the TUBS Technical University of Braunschweig

6.6 Energetically autonomous operation: Energy demand and energy consumption

When evaluating the plant, the actual consumption in electrical energy was also studied.
In addition to this the potential production of electrical energy from the biogas produced was investigated and compared to the consumption observed.
This led to the conclusion that the potential electrical energy production was in total slightly higher than the amount which was demanded.

This result confirmed the design work, which predicted that the plant could be operated autonomously if biogas was used for electrical energy production and which therefore foresaw the implementation of a biogas-engine-generator set.

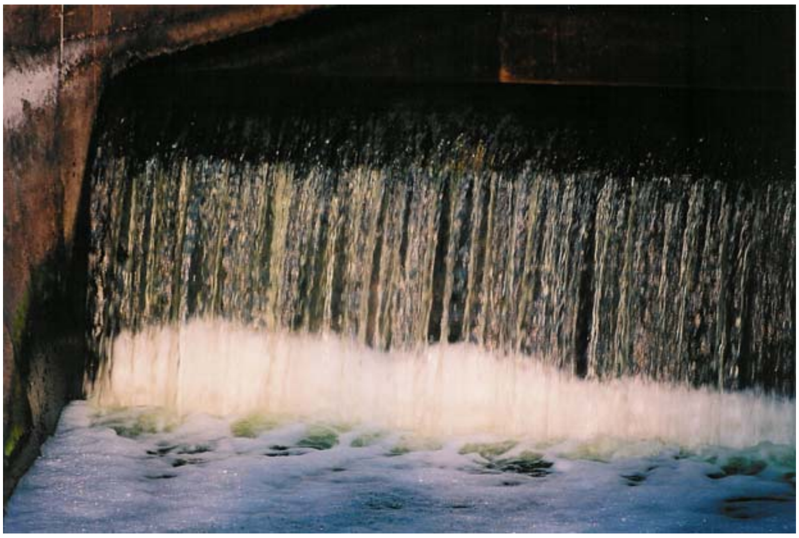

Fig. 22: Pond effluent

Fig. 19 proves clearly that the biogas obtained can be used energetically and eliminated the doubts that existed or were distributed intentionally at political level.

6.7 Landscaping

When constructing the plant it was the aim of the Consultant to harmonize its appearance as much as possible with that of the landscape which existed at the banks of the Babahoyo River by choosing an adequate ecological engineering design and to cause no permanent disturbance.

Fig. 23: Coots and shorebirds

Much attention was paid to make use of concrete in a reluctant manner, while constructing the different works and to cover them as far as possible with soil (Fig. 8,9) or even to make them disappear below ground. Thereafter ecosystems were constructed, - among other measures – by planting a considerable amount of endemic vegetation.
If one creates the total engineering project as it happened here as well as at other locations also considering ecological and landscaping aspects, then biotopes can be created characterized by high biodiversity (Fig. 1 to 6, 10-12, 14, 23-25), which radiate a natural aura.

In this manner in principle natural paradises can be re-created.

7 Summary, Recommendations

After finalizing a period of three years of operation and evaluation it can be said:

The plant fulfilled all expectations formulated and laid down in the target specifications during the stage of design.

The Consultant recommends in the interest of dissemination of this technology to consequently further improve the envelope of obligations which had been originally defined. To this belongs:

- To make use of the bio-energy produced,
  - instead of emitting the biogas unutilized into the atmosphere and thus
  - contributing unnecessarily in this manner to global warming.
- To also make use of the sludge by applying it according to the demand and the needs of the plants in agriculture as well as forestation.
- To use the ponds for fish farming or
- to produce and harvest plankton including algae for the generation of bio-energy.
- With regard to the operation of the plant: The plant has to be run in a way that the pumps are working continuously and the weirs are equipped with throttles.

- From the technical point of view it makes sense, to operate the anaerobic reactors again during a period of six months under identical conditions as it was done during Phase III, in order to obtain much more precise process data, as well as additional information about special operation conditions like short retention times and high volumetric loading rates.

Fig. 24: Wastewater pond system with selected fauna and flora

The plant delivers daily a magnitude of information, e.g. about the conversion of phosphorous and nitrogen, the production of biogas and the degradation of germs. These data are of high value with regard to the further improvement of the anaerobic high-rate process and the total pond system as such. They can be evaluated only in a minor range by the operator, as his interest because of economic constraints has to focus on the plant operation and not on further research and development.
In this project the limited budget was sufficient to obtain insight into the behaviour of the plant during operation conditions of this new, innovative and well suited technology, which was adapted to and optimized according to the local practical conditions.
In view of the dissemination of this technology it would for sure be desirable, if these activities could be continued more deeply during a defined period within the framework of an international scientific cooperation.
It would also be desirable, if the design and construction of such plants would be supported like in this case in the future by international development banks.
The consideration of landscape ecology after construction of the plant contributed to the rehabilitation and preservation of the existing ecosystems of the region.
Because of the close cooperation between all stakeholders, the citizens of Babahoyo, the Ecuadorian institutions and administration like MIDUVI and EMSABA, the Consultant, the constructors, the GTZ (now GIZ) and the KfW, an element of outstanding importance of the urban infrastructure of Babahoyo could be created by construction of this plant. It improves in combination with the embankment, road construction and other works designed and installed under the supervision of the Consultant in the fields of general water management, sanitation and urban planning obviously the local living conditions of the citizens of Babahoyo as well.
Nowadays living in Babahoyo can mean living a quality life.

8 References

Photographs
All pictures were taken by the author at the site of the wastewater treatment plant of Babahoyo, except Fig. 4.

Literature

[1] Kloss, R.: *Pond systems of the second generation.* Second International Water Conference (IWA 2001). 15. bis 18. Oktober 2001, Berlin

[2] Kloss, R.: *Tratamiento Anaérobico de Aguas Negras Domésticas y del Beneficio de Café.* Biogas Seminar Lateinamerika und Karibik, Cali, Kolumbien. 20. - 24.6.1988, Hrsg. GTZ, Eschborn.

Fig. 25: The X-snake “Serpiente equis” (Bothrox atrox)

[3] Kloss, R. und L. Vargas: *Difusión de la Tecnología de Biogas. Informe de actividades.* Reporte Final, Convenio Colombo-Alemán de Cooperación Técnica. PN 81.2009.9-03.100, Marzo 1989, Santiago de Cali, Kolumbien, unveröffentlicht.

[4] Kloss, R.: *Tratamiento Anaérobico de Sustratos Altamente Contaminados con un Gran Porcentaje de Materia Sólida Gruesa en Suspensión.* 5. - 9.12.88, Ciudad Antigua, Guatemala. ICAITI, Guatemala, Hrsg. ICAITI, Guatemala, 1990

[5] Kloss, R.: *Stand, Potentiale und Bedeutung der Biogastechnologie auf dem Gebiet der anaeroben Reinigung von dünnflüssigen Abwässern sowie Maßnahmen zur Einführung dieser Technologie in den ländlichen Regionen der Dritten Welt.* Studie im Auftrag der GTZ. PN 80.2224.6-09.100. Biogasverbreitungsprogramm - überregional -Braunschweig - Königslutter, Mai 1990

[6] Kloss, R.: *Planung, Bau und Betrieb einfacher Hochleistungsanlagen zur anaeroben Reinigung von Abwässern.* Tagungsbericht Biogasseminar Oberreifenberg "10 Jahre GATE/GTZ Biogasverbreitungsprogramm". Hrsg. GTZ, Eschborn, 1990

[7] Kloss, R.: *High-rate plants for anaerobic treatment of waste water and production of biogas.* Biogas Forum (ISSN: 0936-8728), Nr.4, 1991/1.

[8] Kloss, R.: *Determination of performance and limits of technical and economical application of different anaerobic digesters for the treatment of wastewaters with a high portion of coarse suspended solids.* Sixth International Symposium on Anaerobic Digestion, poster papers. Sao Paulo, Brasilien, Mai 1991.

[9] Kloss, R.: *Abwassertechnik global.* Schriftenreihe des Institutes für Siedlungswasserwirtschaft der Technischen Universität Braunschweig. 2. Auflage. 2002, Braunschweig. http://opus.tu-bs.de/opus/volltexte/2002/292

[10] Kloss, R.: *Neue Verfahren und Reaktoren zur anaeroben Behandlung von Schlämmen und Abwässern mit hohem Anteil an groben suspendierten Feststoffen im Vergleich Teil I: Schlämme Teil II: Abwässer.* Schriftenreihe des Institutes für Siedlungswasserwirtschaft der Technischen Universität Braunschweig. ISSN 0934-9731. 2002, Braunschweig. http://opus.tu-bs.de/opus/volltexte/2003/398

[11] Haskoning, Universidad del Valle/Cali, Universidad de Agronomia de Wageningen, INCOL: *Tratamiento anaerobico y reuso de aguas residuales domesticas.* Estudio Planta de Prueba. 1986, Santiago de Cali/Colombia

[12] Universidad del Valle/Cali, Corporación Autónoma Regional del Cauca (CVC), Universidad de Agronomia de Wageningen:
Arranque y operación de sistemas de flujo ascendente con manto de lodo
1987, Santiago de Cali/Colombia

[13] ATV: *Grundsätze für Bemessung, Bau und Betrieb von Abwasserteichen für kommunales Abwasser. Arbeitsblatt A 201.* 2. Auflage 1989. Regelwerk der Abw. Techn. Vereinigung

[14] Neumann, H.: *Unbelüftete Abwasserteiche. Darstellung der naturwissenschaftlichen Verfahrensgrundlagen und Bericht über Erfahrungen aus Niedersachsen*. Schriftenreihe des Niedersächsischen Städte- und Gemeindebundes, Heft 5, Abwasserklärteiche. Hildesheim, 1983

[15] Galagan, James E. et al: *The Genome of Methanosarcina acetivorans Reveals Extensive Metabolic and Physiological Diversity*. Vol. 12, Issue 4, 532-542, April 2002. Genome research, Cold Spring Harbor Laboratory Press, ISSN 1088-9051/02

[16] Broad Institute: *Methanosarcina acetivorans (C2A) Database.* 2004 Cambridge/USA

[17] CES Consulting Engineers Salzgitter GmbH: *Memoria de Diseño Definitivo.* Junta Nacional de la Vivienda, JNV. Kreditanstalt für Wiederaufbau, KfW. Programa de Desarollo Urbano de Babahoyo. Guayaquil/Ecuador-Salzgitter Bad/Germany, 1992

[18] MAE: *Norma de calidad ambiental y descarga de efluentes*. Agosto 2002. Quito, Ecuador

[19] CES Consulting Engineers Salzgitter GmbH: *Programa de asesoramiento en la Puesta en Marcha de la Planta de Tratamiento de Aguas Servidas.* Informe final. Ministerio Urbano y Vivienda (MIDUVI). Empresa de Saneamiento Ambiental de Babahoyo (EMSABA). Kreditanstalt für Wiederaufbau (KfW). Programa de Desarollo Urbano de Babahoyo. Guayaquil/Ecuador-Salzgitter Bad/Germany, (in Vorbereitung) 2004

[20] Prasitpianchai, S., C. Sawatdeenarunat, U. Kantha and N. Tovivek:
Improve biogas plant performance through capacity building for operators
in:
Biogas Engineering and Application, Volume 2, p. 50 to 56
Eds.: Renjie Dong and Bernhard Raninger, Beijing, December 2011, ISBN 978-7-5655-0497-6

[21] BIOMA Biogas Institute of Agriculture: *Training Course on BiogasTechnology*, APEC & BIOMA, 26th of November until 2nd of December, 2012, Chengdu, China

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